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Longitudinal discharge pumped low-pressure XeCl laser

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***Abstract*. We have studied output parameters of a XeCl and a N_2 laser pumped by a longitudinal discharge with automatic spark UV preionisation. The output parameters of a low-pressure (30 Torr) XeCl laser operating with Ar, Ne and He as buffer gases or with no buffer gas have been optimised for the first time. The laser generated 5-ns FWHM pulses with an average power of 0.5 mW and output energy of 0.15 mJ. Under longitudinal discharge pumping, an output energy per unit volume of 1.8 J L^{-1} atm^{-1} was reached using helium as a buffer gas. With argon-containing and buffer-free mixtures, it was 1.5 J L^{-1} atm^{-1}. The N_2 laser generated 2.5-ns FWHM pulses with an average power of 0.35 mW and output energy of 0.05 mJ.**

Keywords: *longitudinal excitation discharge, UV-preionised nitrogen and excimer lasers, UV radiation.*

1. Introduction

Miniature excimer UV lasers typically employ a transverse excitation discharge and additional UV preionisation sources [1, 2]. At the same time, longitudinal discharge pumping has a number of advantages: a simple and reliable laser design, round input beam cross section and high beam homogeneity, which corresponds to a low beam divergence [3]. Isakov et al. [4] were the first to demonstrate the possibility of using a longitudinal discharge for the excitation of excimer molecules, including XeF*. They obtained an output energy of 0.12 mJ at a gas mixture pressure p = 152 Torr. However, at a high charge voltage V_0 = 120 kV, the energy parameters of the laser output were not good enough. This was related to the large (30 cm) electrode separation in the active gas medium. Newman [5] was the first to demonstrate the possibility of stabilising a longitudinal excitation discharge through UV corona preionisation. He reduced V_0 by a factor of 2 by using two discharge gaps, which were charged in parallel and excited in series. This pumping scheme was referred to as a longitudinal capacitively coupled excitation discharge. Newman [5] obtained KrF* and XeF* lasing with output energies of 0.05 and 0.035 mJ, respectively, at a pressure of 380 Torr. To pump a XeCl laser, Zhou et al. [6] used a sliding surface discharge. It ensured UV preionisation of the active gas medium and then a pump pulse for excitation of the medium. It was shown by Zhou et al. [6] that the output parameters of the laser were an order of magnitude better than those under excitation with a conventional longitudinal discharge. They obtained an output energy of 0.32 mJ at p = 532 Torr and V_0 = 36 kV, whereas with standard electrodes the output energy was 0.03 mJ under the same conditions.

Zubrilin et al. [7] were the first to demonstrate the possibility of lasing of KrF*, XeF* and XeCl* excimer molecules under transverse discharge pumping in mixtures containing no buffer gas. Using a capacitively excited longitudinal discharge, de la Rosa and Eichler [8] obtained an optical output energy of 0.08 mJ from KrF* molecules (with no buffer gas) at V_0 = 84 kV and a gas mixture pressure of 302 Torr. A further improvement of the longitudinal pumping scheme for the XeCl laser was reported by Furuhashi et al. [9]. They employed a number of additional spark UV preionisation sources to stabilise several series-connected longitudinal high-pressure discharges and obtained an optical output energy of 0.1 mJ and pulse duration (FWHM) of 15 ns at p = 1140 Torr and V_0 = 40 kV. The net length of the four-segmented longitudinal discharge was 26 cm.

This paper presents a study of a longitudinal discharge pumped low-pressure XeCl laser with automatic spark UV preionisation sources at varied discharge pulser parameters, with the use of two- or three-component gas mixtures as gain media.

2. Experimental

In our experiments, use was made of a miniature laser system similar to that described by Furuhashi et al. [9]. The gas mixture was contained in quartz tubes 0.4 and 0.5 cm in inner diameter. The tubes had four, longitudinally pumped discharge sections (Fig. 1), each 4 cm in length. Five pairs of 0.2-cm-diameter steel pin electrodes were used. The net length of the discharge channel was thus 16 cm, and the active working volume was variable from 1.6 to 2 cm^3. The cavity was formed by a highly reflective aluminium mirror and a plane-parallel quartz plate. The gain medium was pumped using a Blumlein pulse generator. Its capacitances C_1 and C_2 could be varied from 4 to 9 nF. The optimal charging capacitance of the discharge pulser under our excitation conditions was 12 nF. The capacitor C_3 was used as a peaking capacitor of the laser channel UV preionisation source. Its capacitance could be varied from 0.6 to 1.3 nF. The switch used was an RU-62 commercially available discharge switch, which simplified the excitation circuit and allowed us to obtain better output characteristics than with a thyratron [10].

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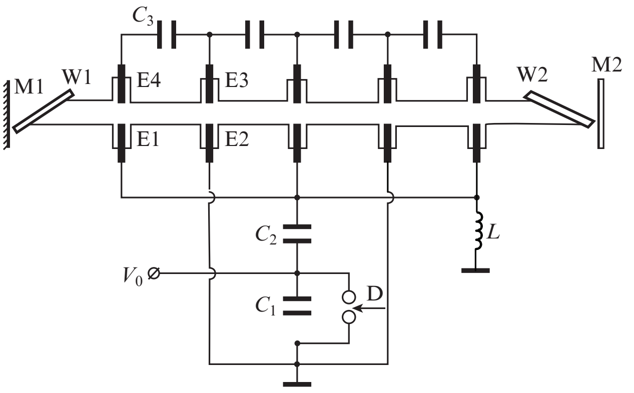

Figure 1. Power supply circuit of the longitudinal-discharge XeCl laser with automatic spark UV preionisation: E1 – E4 are electrodes, C_1 and C_2 are the Blumlein pulser capacitances, C_3 is the peaking capacitance of the longitudinal discharge sections, D is a controlled discharge switch, L is the charging inductance, W1 and W2 are optical mirrors and M1 and M2 are the cavity mirrors.

As an example, consider the operation of a four-electrode excitation module. When the controlled discharge switch D opened, the voltage across the capacitor C_1 was reversed and a rapidly rising high-voltage pulse was applied to the electrode pairs E1 – E4, E2 – E3 etc. through the peaking capacitor C_3. After breakdown of these gaps (which ensured gas ionisation), the peaking capacitor C_3 was simultaneously charged through UV preionisation discharges. After it was charged to the breakdown voltage, a main longitudinal discharge was ensured between the electrodes E3 and E4 along the tube axis. Under appropriate conditions, a discharge was also observed between the electrodes E1 and E2. In this process, the four longitudinal sections operated simultaneously. Our experiments were performed in nitrogen and Xe – HCl and He(Ne, Ar) – Xe – HCl gas mixtures. Laser output parameters were determined using an IMO-2N calorimeter, FEK-22-SPU-M photodiode and Tektronix TDS3032 oscilloscope.

3. Experimental results

To optimise parameters of the laser system, preliminary experiments were performed with molecular nitrogen as a gain medium. The laser output energy parameters were measured as functions of discharge pulser parameters and energy deposited in the discharge. Figure 2a shows the average laser output power as a function of peaking capacitance C_3. The maximum average output power reached 0.35 mW at a peaking capacitance of 0.9 nF, excitation pulse repetition rate f = 10 Hz, V_0 = 12 kV and nitrogen pressure of 40 Torr. The laser pulse duration (FWHM) was 2.5 ns. Following optimisation of discharge pulser parameters, the output energy was measured as a function of charge voltage and gas pressure (Fig. 2b). The optimal nitrogen pressure was 40 Torr, independent of the charge voltage. The output energy was found to increase linearly with V_0. The highest output energy, 0.05 mJ, was reached at V_0 = 13 kV. The lifetime of the nitrogen laser was assessed in sealed-off mode. With one gas portion, the laser stably emitted $\sim 10^5$ pulses, and the maximum pulse repetition rate was 15 Hz. Our results demonstrate that there is a rigid connection between matching of the discharge plasma's wave resistance and the excitation source with automatic UV preionisation. In particular, increasing the nitrogen pressure to above the optimal one (40 Torr) reduced the laser output energy, independent of V_0. In this process, the discharge remained uniform. One distinctive feature of the pumping scheme in question is a low charge voltage, which is considerably lower (by more than a factor of 2) than that used by Furuhashi and Goto [3]. It is known that, in many practical applications, especially in medicine, as low a voltage as possible should be used.

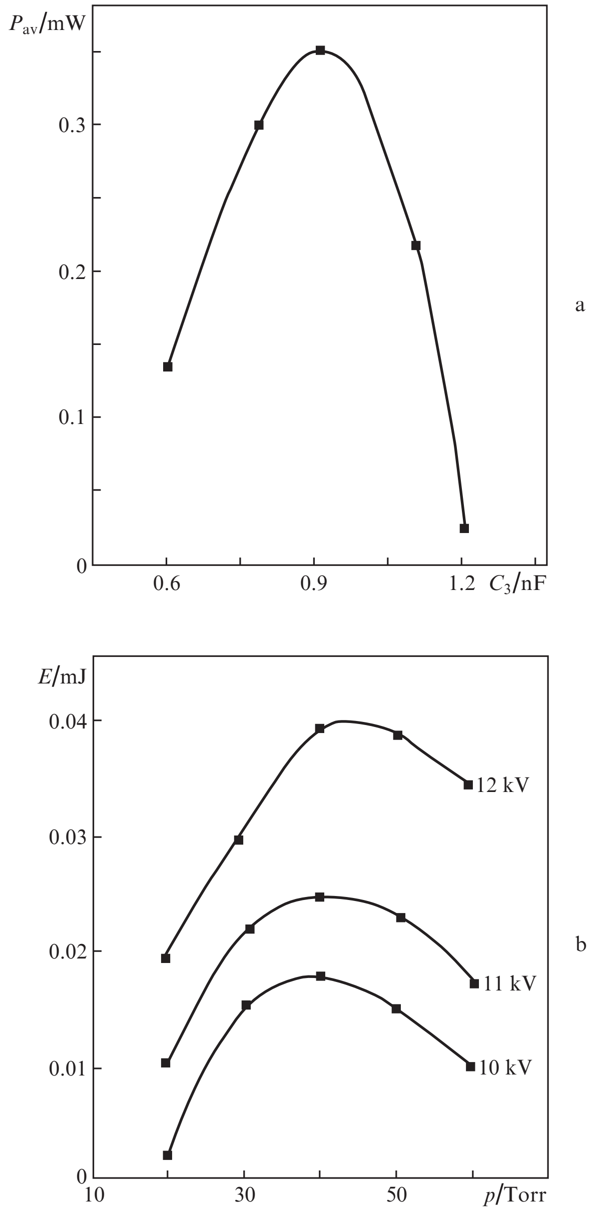

Figure 2. (a) Average output power as a function of peaking capacitance for a nitrogen laser at p = 40 Torr, V_0 = 12 kV and f = 10 Hz; (b) output energy as a function of gas mixture pressure at different charge voltages.

The system under consideration was used to experimentally study a XeCl laser. Figure 3 shows a laser pulse and the laser output energy as a function of gas mixture pressure at different Xe : HCl ratios and constant HCl pressures of 2 and 4 Torr. The laser pulse duration (FWHM) was 5 ns. The buffer gas used was helium. The optimal Xe : HCl ratio was 2 : 1

at p_{HCl} = 4 Torr and 20 : 1 at p_{HCl} = 2 Torr. At p_{HCl} = 4 Torr, the output energy decreased with increasing Xe pressure (Fig. 3a). At low pressures, the major components of the gas mixture were Xe and HCl. Increasing the percentage of helium buffer gas reduced the laser output energy at gas mixture pressures above the optimal 30 Torr. Figure 3b presents analogous data obtained at p_{HCl} = 2 Torr. At Xe : HCl = 5 : 1, the output energy increased by almost a factor of 2. In addition, it increased with increasing helium content at gas mixture pressures below 30 Torr and dropped at higher helium contents. Similar correlations were found at all other ratios of the major components of the gas mixture. At p_{HCl} = 2 Torr, the optimal Xe : HCl ratio was 20 : 1, exceeding that above by ten times, and the laser output energy increased by almost a factor of 2. At low percentages of helium buffer gas, the highest output energy was 0.11 mJ and the peak power was 20 kW. Therefore, when a longitudinal excitation discharge and intense UV preionisation source are used, only the HCl and Xe concentrations play a significant role in the gas mixture. It also follows from the above results that, at HCl pressures of 4 and 2 Torr, the optimal gas mixture pressure is ~30 and 40 Torr, respectively. In the case of the latter gas mixture, the laser output energy was twice that at p_{HCl} = 4 Torr. Among the gas mixtures studied, the highest output energy, 0.15 mJ, was obtained at $p_{HCl} \approx 3$ Torr. It is worth noting that, in the case of fast pumping with a transverse discharge, the optimal p_{HCl} was also 3 Torr [11].

Figure 4 shows the XeCl laser output energy as a function of gas mixture pressure at a varied Xe : HCl ratio, with Ar and Ne as buffer gases. In the case of Ar, the discharge was less uniform at high HCl concentrations. The highest optical pulse energy was 0.07 mJ, at the optimal Xe : HCl ratio of 5 : 1 and a gas mixture pressure of 30 Torr. Similar output characteristics were obtained with Ne. The highest pulse energy was 0.06 mJ, at the optimal Xe : HCl ratio of 5 : 1 and the optimal gas mixture pressure of 30 Torr. Thus, the laser output energy parameters obtained with Ar and Ne as buffer gases were roughly the same and were smaller than those obtained with He. In the case of helium, the optimal Xe : HCl ratio was 20 : 1. Consequently, when longitudinal discharge excitation and an additional spark UV preionisation source were used, better output characteristics were obtained with helium as a buffer gas or without helium under fast pumping. This was probably due to the large E/p ratios (100 V cm^{-1} Torr^{-1}) and high pump power densities (~2–3 MW cm^{-3}). In such a discharge, a buffer gas does not play any significant role in dis-

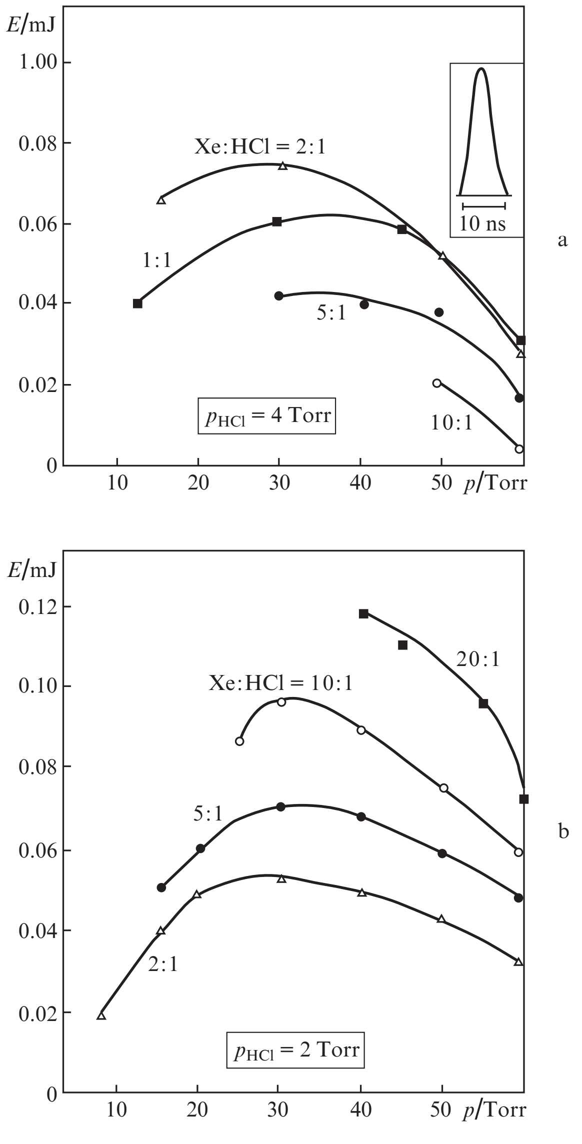

Figure 3. XeCl laser output energy as a function of He–Xe–HCl gas mixture pressure at different Xe : HCl ratios, V_0 = 12 kV and p_{HCl} = (a) 4 and (b) 2 Torr. Inset: XeCl laser pulse.

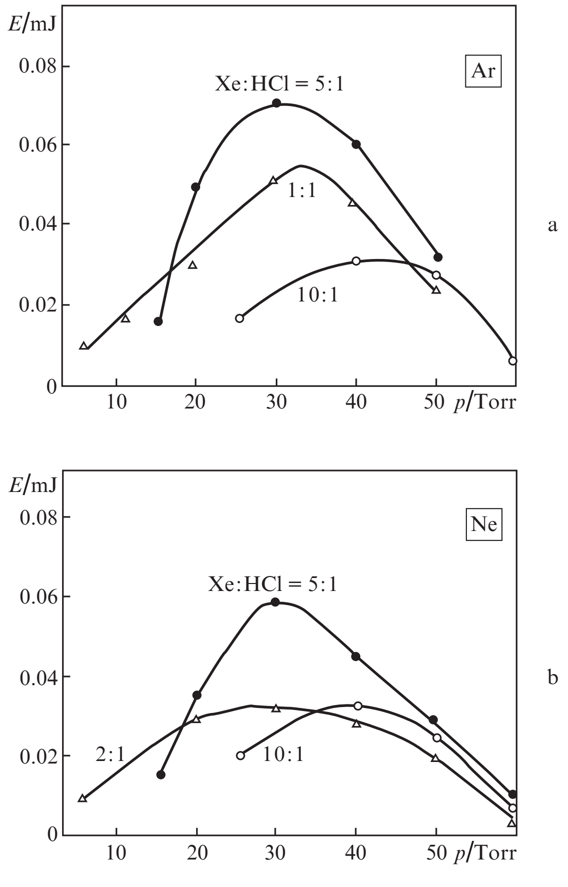

Figure 4. XeCl laser output energy as a function of gas mixture pressure at a varied Xe : HCl ratio, with (a) Ar and (b) Ne as buffer gases; V_0 = 12 kV, p_{HCl} = 2 Torr.

charge development stabilisation or in an extra channel for the formation of working molecules, in contrast to transverse discharge excited high-pressure lasers [12–15].

Figure 5 summarises the present results for the XeCl laser in the form of the average output power as a function of gas mixture pressure (Xe : HCl = 5 : 1; $p_{\rm HCl}$ = 2 Torr; Ar, Ne and He buffer gases) and the laser output energy as a function of Xe pressure at the optimal HCl : He ratio of 1 : 1 and HCl pressures of 2 and 4 Torr. In the longitudinal pumping mode under consideration, the optimal pressure at Xe : HCl = 5 : 1 was 30 Torr. The buffer gas concentration then only slightly exceeded the concentrations of the major components of the gas mixture. Lasing of XeCl* molecules at low pressures with no buffer gas was observed for the first time. Increasing the buffer gas pressure reduced the laser output energy, independent of the buffer gas. The corresponding curves are similar in shape, suggesting that the same mechanism was responsible for the excitation of XeCl molecules. The best output parameters were obtained with helium. The roles of Xe and HCl are best illustrated by the results obtained at HCl : He = 1 : 1 and $p_{\rm HCl}$ = 2 and 4 Torr. At low HCl contents, the output energy rises almost linearly with increasing Xe concentration. It seems likely that Xe acts as a buffer gas as well. At a high HCl pressure (4 Torr) and Xe : HCl = 2 : 1, the output energy has a maximum. With increasing Xe pressure, the output energy decreases monotonically because of the increasing discharge instability.

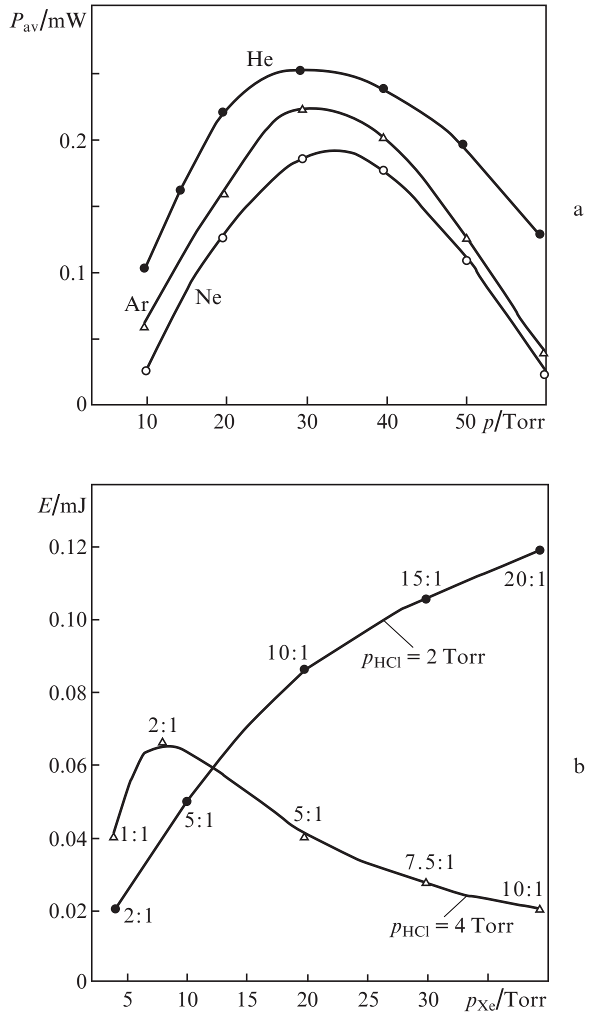

Figure 5. (a) Average XeCl laser output power as a function of gas mixture pressure at Xe : HCl = 5 : 1 ($p_{\rm HCl}$ = 2 Torr), f = 3 Hz and V_0 = 12 kV, with Ar, Ne and He as buffer gases. (b) Laser output energy as a function of Xe pressure for He–Xe–HCl mixtures (He : HCl = 1 : 1) at V_0 = 12 kV and $p_{\rm HCl}$ = 2 and 4 Torr.

Thus, the use of a Blumlein pulse generator and the optimisation of its parameters and the gas mixture composition in the XeCl laser allowed us to reduce the charge voltage by more than a factor of 3, the gas mixture pressure by more than one order of magnitude and the active laser channel length by a factor of 1.5 with respect to previous results [9]. Moreover, the laser output energy was a factor of 1.5 higher in this study. In addition, using helium as a buffer gas, we obtained an output energy per unit volume of 1.8 J L^{-1} atm^{-1}, comparable to that under transverse discharge pumping, which ensures high excitation power densities. According to Razhev et al. [16], for efficient excitation of a KrF laser by a fast transverse discharge in mixtures containing helium as a buffer gas, one should use high pump power densities, $W = E_{\rm c}/(V\tau)$, where $E_{\rm c}$ is the energy stored in the peaking capacitor; V is the active laser volume; and τ is the duration of the first discharge current half-period. In their study, a pump power density of 4 MW cm^{-3} was ensured under optimal excitation of the KrF laser [16]. In our case, the pump power density of a XeCl laser with an active volume of 2 cm^3, peaking capacitance of 0.9 nF, charge voltage V_0 = 12 kV and first discharge current half-period duration of 10 ns was 3.3 MW cm^{-3}. In the case of the gas mixtures containing Ar as a buffer gas, the output energy per unit volume reached 1.5 J L^{-1} atm^{-1}, which corresponds to that of the mixtures containing no buffer gas.

4. Conclusions

We have studied for the first time and optimised output parameters of a longitudinal-discharge low-pressure (30 Torr) XeCl laser using Ar, Ne and He as buffer gases. The results indicate that the laser can effectively operate with no buffer gas. This allows one to obtain new data for evaluating the kinetics of self-sustained discharge excited excimer lasers. A benchtop laser generated 5-ns FWHM pulses at a repetition rate of 15 Hz and charge voltages of up to 13 kV with an average power of 0.5 mW and output energy of 0.15 mJ. Under longitudinal discharge pumping, an output energy per unit volume of 1.8 J L^{-1} atm^{-1} was reached for the first time using helium as a buffer gas. With argon-containing and buffer-free mixtures, it was 1.5 J L^{-1} atm^{-1}. In addition, we studied output parameters of a N_2 laser, which operated at a pressure of 40 Torr, pulse repetition rate of 15 Hz and charge voltage of 13 kV. It generated 2.5-ns FWHM pulses with an average power of 0.35 mW and output energy of 0.05 mJ.

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